

Simplified TeV leptophilic dark matter in light of DAMPE data

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ABSTRACT: Using a simplified framework, we attempt to explain the recent DAMPE cosmic $e^+ + e^-$ flux excess by leptophilic Dirac fermion dark matter (LDM). The scalar (Φ_0) and vector (Φ_1) mediator fields connecting LDM and Standard Model particles are discussed. We find that the couplings $P \otimes S$, $P \otimes P$, $V \otimes A$ and $V \otimes V$ can produce the right bump in $e^+ + e^-$ flux for a DM mass around 1.5 TeV with a natural thermal annihilation cross-section $\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$ today. Among them, $V \otimes V$ coupling is tightly constrained by PandaX-II data (although LDM-nucleus scattering appears at one-loop level) and the surviving samples appear in the resonant region, $m_{\Phi_1} \simeq 2m_\chi$. We also study the related collider signatures, such as dilepton production $pp \rightarrow \Phi_1 \rightarrow \ell^+ \ell^-$, and muon $g-2$ anomaly. Finally, we present a possible $U(1)_X$ realization for such leptophilic dark matter.

KEYWORDS: Phenomenological Models

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1 Introduction

The existence of cold dark matter (CDM) has been confirmed by astrophysical experiments, which provides a natural way to account for many properties of galaxies on large scales. However, the nature of CDM has remained elusive. Among various hypotheses for CDM, the paradigm of weakly interacting massive particles (WIMPs) is one of the most attractive candidates. So far, the WIMP dark matter has undergone very close and effective experimental scrutiny, such as direct detections by measuring the nuclear recoil imparted by the scattering of a DM and collider searches for mono- X signatures.

Besides these, indirect detections via observing high energy gamma-rays, cosmic-rays and neutrinos may also shed light on the properties of DM. In past years, several DM satellite experiments, such as AMS-02, PAMELA, HEAT and Fermi-LAT, have been launched and reported some intriguing DM evidences. The Dark Matter Particle Explorer (DAMPE) is a new cosmic ray detector [1, 2], which has great energy resolution (better than 1.5%@TeV for electrons and gamma rays) and good hadron rejection power (higher than 10^5). Very recently, DAMPE released their first results about cosmic-ray $e^+ + e^-$ flux up to 5 TeV [3]. A sharp peak at ~ 1.4 TeV was reported in DAMPE data, which implies the existence of a nearby monoenergetic electron sources because of the cooling process of high energy cosmic-ray electrons [4, 5]. No associated excess in the anti-proton flux has been observed. Both astrophysical sources (e.g., pulsars) and DM interpretations are discussed in ref. [4]. It is found that DM should annihilate to e^\pm or $\{e^\pm, \mu^\pm, \tau^\pm\}$ with 1:1:1 and the mass of DM particle is about 1.5 TeV if the nearby DM sub-halo located at $0.1 \sim 0.3$ kpc away from the solar system [4]. Several leptophilic DM model have been proposed to explain this excess [6, 7].

In this work, we attempt to explain this tentative cosmic-ray electron+positron excess by using a simplified framework, in which the DM sector has no direct couplings to quarks, only couples with leptons mediated by a scalar or vector field. Such a leptophilic DM can satisfy the measured relic density at tree level and may accommodate the null results from direct detections by inducing interactions between dark matter and quarks at the loop level. Many studies have been devoted into the idea that DM does not interact with quarks at

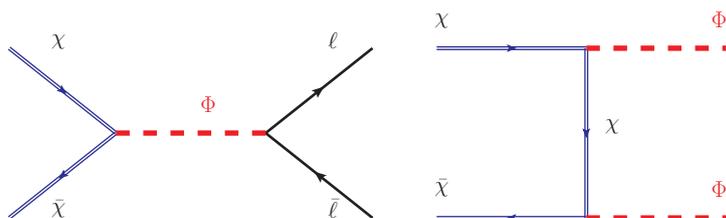


Figure 1. Feynman diagrams for LDM annihilation.

the tree level. Most of these analyses assume an interaction between DM and leptons to be flavor blind [8, 8–39], while a few other studies assume gauged flavor interactions [33, 40–48]. The leptophilic DM framework allows for a more general analysis of interactions that involve only DM and leptons at the tree level. It permits different coupling strengths between lepton flavors, off-diagonal flavor couplings, and lepton-flavor violation.¹

The structure of this paper is organized as follows. In section 2, we introduce the effective lagrangian for leptophilic DM and loop induced LDM-hadron interactions. In section 3, we present our numerical results for the DAMPE excess and discuss the related collider signatures. In section 4, we give a possible realization of leptophilic DM in U(1) extensions. Finally, we draw our conclusions in section 5.

2 Simplified leptophilic dark matter

The main goal of our study is a model independent analysis of leptophilic Dirac fermion DM (χ) for the DAMPE excess. We parameterize the relevant DM-lepton interactions as

$$\mathcal{L} \ni \Phi_i \bar{\chi} \Gamma_\chi \chi + \Phi_i \bar{\ell} \Gamma_\ell \ell, \quad (2.1)$$

where Φ_i is a mediator field with $i = 0, 1$ corresponding to spin-0 and spin-1 boson respectively. We assume that Φ_i only couples with leptons e, μ, τ in our calculations. Then, the Lorentz structures of $\Gamma_{\chi, \ell}$ are scalar (S), pseudo-scalar (P), vector (V) and axial-vector (A) interactions given by

$$\begin{aligned} \text{scalar-type:} \quad & \Gamma_\chi = g_\chi^S + i g_\chi^P \gamma_5, & \Gamma_\ell = g_\ell^S + i g_\ell^P \gamma_5, \\ \text{vector-type:} \quad & \Gamma_\chi^\mu = (g_\chi^V + g_\chi^A \gamma_5) \gamma^\mu, & \Gamma_{\ell\mu} = (g_\ell^V + g_\ell^A \gamma_5) \gamma_\mu, \end{aligned} \quad (2.2)$$

where g_χ and g_ℓ are the coupling strengthes of the mediator to DM and SM leptons, respectively.

In our framework, the dominant LDM annihilation channels are

$$\chi \bar{\chi} \rightarrow \ell \bar{\ell}, \Phi \Phi \quad (2.3)$$

with the corresponding Feynman diagrams in figure 1. For a pair of LDM, the CP value of the system is given by $(-1)^{S+1}$. Due to the CP and total angular momentum conservation,

¹For a review of flavored dark matter, see ref. [49] and the references therein.

$\Gamma_\chi \otimes \Gamma_\ell$	$\sigma v(\chi\chi \rightarrow \ell\bar{\ell})$	$\sigma(\chi N \rightarrow \chi N)/(\frac{\alpha_{em} Z}{\pi m_\Phi^2})^2$	
$S \otimes S$	p -wave	α_{em}^2	[2-loop]
$S \otimes P$	p -wave	—	
$P \otimes S$	s -wave	$\alpha_{em}^2 v^2$	[2-loop]
$P \otimes P$	s -wave	—	
$V \otimes V$	s -wave	1	[1-loop]
$V \otimes A$	s -wave	—	
$A \otimes V$	p -wave	v^2	[1-loop]
$A \otimes A$	p -wave	—	

Table 1. Dominant contribution to LDM annihilation cross section and scattering cross section suppression by small parameters for loop induced DM-nucleon scattering for eight Lorentz structures. Here v is the DM velocity.

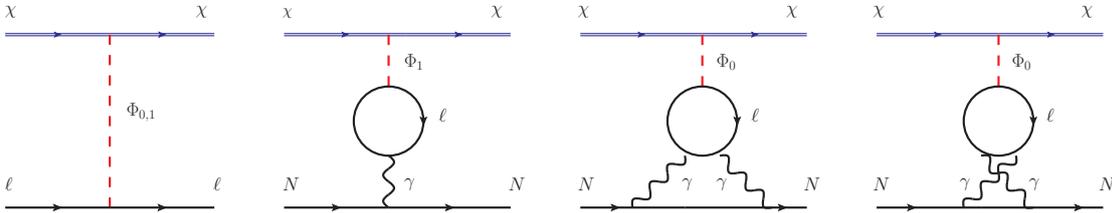


Figure 2. Feynman diagrams for LDM scattering with electron and nucleus.

the quantum states of $|\bar{\chi}\chi\rangle$ are 3P and 1S for the scalar and pseudoscalar mediators, while the corresponding states for vector and axial-vector mediators are 3S and 1P , respectively. Then, one can estimate the dominant contributions of LDM annihilation cross section, as shown in table 1. It should be noted that the coupling $A \otimes A$ can produce the s -wave contribution, however, which is highly suppressed by mass ratio m_ℓ^2/m_Φ^2 .

Since the LDM only interacts with leptons, it can produce the signal by scattering with electron of atom at tree level or with nucleus at loop level in DM direct detection experiments, as shown in figure 2. The velocity of DM particles near the Earth is of the same order as the orbital velocity of the Sun, $v \sim 0.001c$. So the recoil momenta is of order a few MeV, which is much smaller than our mediator mass. Then, we can integrate out heavy mediator fields and obtain the effective operators:

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2} (\bar{\chi}\Gamma_\chi\chi) (\bar{\ell}\Gamma_\ell\ell), \quad (2.4)$$

where $\Lambda = m_\Phi/\sqrt{g_\chi g_\ell}$ is the cut-off scale for the effective field theory description. With this setup, one can calculate DM-electron scattering cross section at tree level:

$$\sigma_{\chi e}^{\Phi_0} = \frac{m_e^2 g_\chi^2 g_\ell^2}{m_{\Phi_0}^4} \left\{ (g_\chi^S g_e^S)^2 + \left[(g_\chi^S g_e^P)^2 + (g_\chi^P g_e^S)^2 \frac{m_e^2}{m_\chi^2} \right] \frac{v^2}{2} + \frac{(g_\chi^P g_e^P)^2}{3} \frac{m_e^2}{m_\chi^2} v^4 \right\}, \quad (2.5)$$

$$\sigma_{\chi e}^{\Phi_1} = \frac{m_e^2 g_\chi^2 g_\ell^2}{m_{\Phi_1}^4} \left\{ (g_\chi^V g_e^V)^2 + 3(g_\chi^A g_e^A)^2 + [(g_\chi^V g_e^A)^2 + 3(g_\chi^A g_e^V)^2] \frac{v^2}{2} \right\}. \quad (2.6)$$

We can find that DM-electron scattering cross sections for $S \otimes P$, $P \otimes S$ and $P \otimes P$ couplings are suppressed by both small mass ratio m_e/m_χ and low velocity $v \sim 10^{-3}$, while for $V \otimes A$ and $A \otimes V$ couplings the cross sections are only suppressed by velocity. All of them are below the current sensitivity of DM-electron scattering experiments.

The loop induced DM-nucleus scattering cross sections for spin-1/0 mediator at one-loop/two-loop level in leading log approximation [50] are given by:

$$\sigma_{\chi N}^{\Phi_0} = \frac{\mu_N^2}{\pi} \left(\frac{\alpha_{em} Z}{\pi m_{\Phi_0}^2} \right)^2 \left(\frac{\alpha_{em} Z}{\pi} \right)^2 \left(\frac{\pi^2}{12} \right)^2 \left(\frac{\mu_N v}{m_\ell} \right)^2 \left[2 (g_\chi^S g_\ell^S)^2 + \frac{4}{3} (g_\chi^P g_\ell^S)^2 v^2 \frac{\mu_N^2}{m_N^2} \right] \quad (2.7)$$

$$\sigma_{\chi N}^{\Phi_1} = \frac{\mu_N^2}{9\pi} \left(\frac{\alpha_{em} Z}{\pi m_{\Phi_1}^2} \right)^2 \left[\sum_{\ell=e,\mu,\tau} \log \left(\frac{m_\ell^2}{\mu^2} \right) \right]^2 \left[(g_\chi^V g_\ell^V)^2 + (g_\chi^A g_\ell^V)^2 v^2 \left(1 + \frac{1}{2} \frac{\mu_N^2}{m_N^2} \right) \right] \quad (2.8)$$

where m_N and Z are the nucleus's mass and charge respectively, and $\mu_N = \frac{m_\chi m_N}{m_\chi + m_N}$ is the reduced mass of DM-nucleus system. The above two-loop result of $\sigma_{\chi N}^{\Phi_1}$ is obtained by using operator product expansion in heavy lepton approximation. We set the renormalization scale $\mu = m_\Phi$ and both nuclear form factors $F(q)$ for Φ_1 and $\tilde{F}(q)$ for Φ_0 to unity for simplicity. According to eq. (2.7) and (2.8), we present the scattering cross section suppression by small parameters for loop induced DM-nucleon scattering for eight Lorentz structures in table. 1. It can be seen that the DM-nucleus scattering cross sections for $P \otimes S$ and $A \otimes V$ couplings are suppressed by v^2 , as comparison with $S \otimes S$ and $V \otimes V$ couplings.

3 Numerical results and discussions

According to the analysis of ref. [4], the excess of $e^+ + e^-$ flux in DAMPE can be interpreted by a DM particle with the mass about 1.5 TeV if the nearby DM sub-halo locates at 0.1 \sim 0.3 kpc away from the solar system. We fit the AMS-02 and DAMPE data assuming the DM annihilate into leptons with the branching ratio $e : \mu : \tau = 1 : 1 : 1$. Such a condition can evade the constraints from CMB and the diffuse gamma rays from dwarf spheroidal galaxies (dSphs) [4]. In the fitting, we used numerical codes are GALPROP [51] and DRAGON [52] to calculate the propagation of CR electrons/positrons in the galaxy. We use the analytical solution presented in ref. [53] to calculate the propagation of nearby CR electrons. In the first step, we use the LikeDM package [54] to calculate the likelihood (or χ^2) and fit the AMS-02 and DAMPE data with power-lower background and extra astronomy contribution (see [55] for more details). Then we add the contribution of local DM halos directly as the local CR source only contributes the region around 1.5 TeV. The fitting result is shown in figure 3, in which the mass of DM particles is assumed as 1.5 TeV with the annihilation cross section $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ and the mass of nearby subhalo is $1 \times 10^8 m_\odot$ with a distance 0.1 kpc away from the solar system.

In order to satisfy DM annihilation cross section, $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$, required by DAMPE data, we focus on $P \otimes S$, $P \otimes P$, $V \otimes A$ and $V \otimes V$ couplings which can produce s -wave contributions in our following study. In the following calculations, we assume a universal coupling of the mediator and three generation leptons, $g_\ell = g_e =$

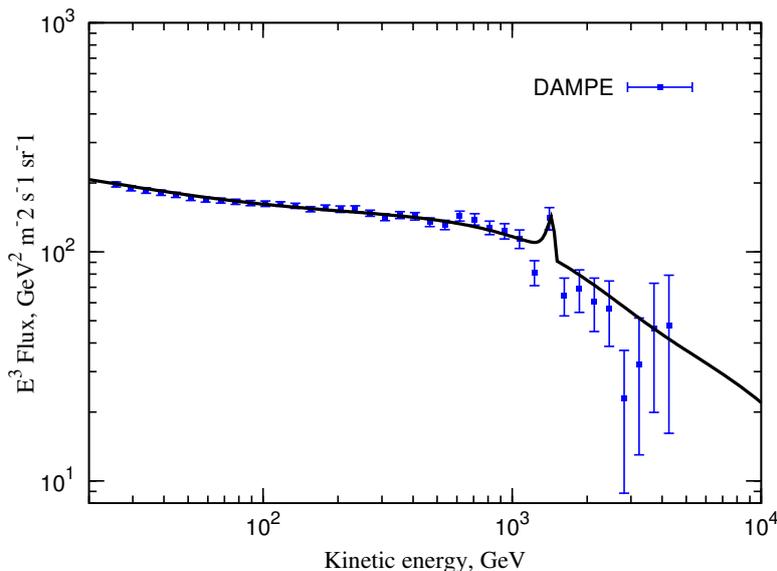


Figure 3. Total $e^+ + e^-$ flux of 1.5 TeV DM that annihilates into leptons with the branching ratio $e : \mu : \tau = 1 : 1 : 1$ for fitting AMS-02 AND DAMPE data. The mass of nearby subhalo is assumed as $1 \times 10^8 m_\odot$ with a distance 0.1 kpc away from the solar system.

$g_\mu = g_\tau$. We implement our leptophilic DM model by using FeynRules [56] and evaluate the DM relic density and annihilation cross section with MicrOMEGAs [57]. Since the mediators can induce the process $e^+e^- \rightarrow \ell^+\ell^-$, they are strongly constrained by LEP measurements of four-lepton contact interactions [58] and di-lepton resonance searches in $e^+e^- \rightarrow \ell^+\ell^-\gamma$ [59]. According the analysis in ref. [60], one can derive the following bounds of the coupling and mass of mediators $\Phi_{0,1}$ at 90% C.L.,

$$g_\ell^V/m_{\Phi_1} < \begin{cases} 2.0 \times 10^{-4} \text{GeV}^{-1}, & m_{Z'} > 200 \text{ GeV} \\ 6.9 \times 10^{-4} \text{GeV}^{-1}, & 100 \text{ GeV} < m_{Z'} < 200 \text{ GeV} \end{cases} \quad (3.1)$$

$$g_\ell^A/m_{\Phi_1} < \begin{cases} 2.4 \times 10^{-4} \text{GeV}^{-1}, & m_{Z'} > 200 \text{ GeV} \\ 6.9 \times 10^{-4} \text{GeV}^{-1}, & 100 \text{ GeV} < m_{Z'} < 200 \text{ GeV} \end{cases} \quad (3.2)$$

$$g_\ell^{S,P}/m_{\Phi_0} < \begin{cases} 2.7 \times 10^{-4} \text{GeV}^{-1}, & m_{Z'} > 200 \text{ GeV} \\ 7.3 \times 10^{-4} \text{GeV}^{-1}, & 100 \text{ GeV} < m_{Z'} < 200 \text{ GeV} \end{cases} \quad (3.3)$$

In figure 4 we project the samples satisfying the requirements of DM relic density within 2σ range of Planck observed value, LEP bound and the DAMPE excess on the plane of g_χ versus m_Φ for different values of g_ℓ . All samples are required to produce averaged annihilation cross-section $\langle\sigma v\rangle$ today within $(2 - 4) \times 10^{-26} \text{cm}^3/\text{s}$. When the mass of DM is close to $m_\Phi/2$, DM annihilation cross section will be enhanced by resonance effect. In order to satisfy the DM relic density requirement, the couplings g_χ^V and g_ℓ^V have to become small, which will suppress the DM-nucleus scattering cross section so that the PandaX-II bound can be evaded [61]. For $P \otimes S$ coupling, the DM-nucleus scattering cross section is highly reduced due to two-loop suppression, while for $P \otimes P$ and $V \otimes A$ couplings,

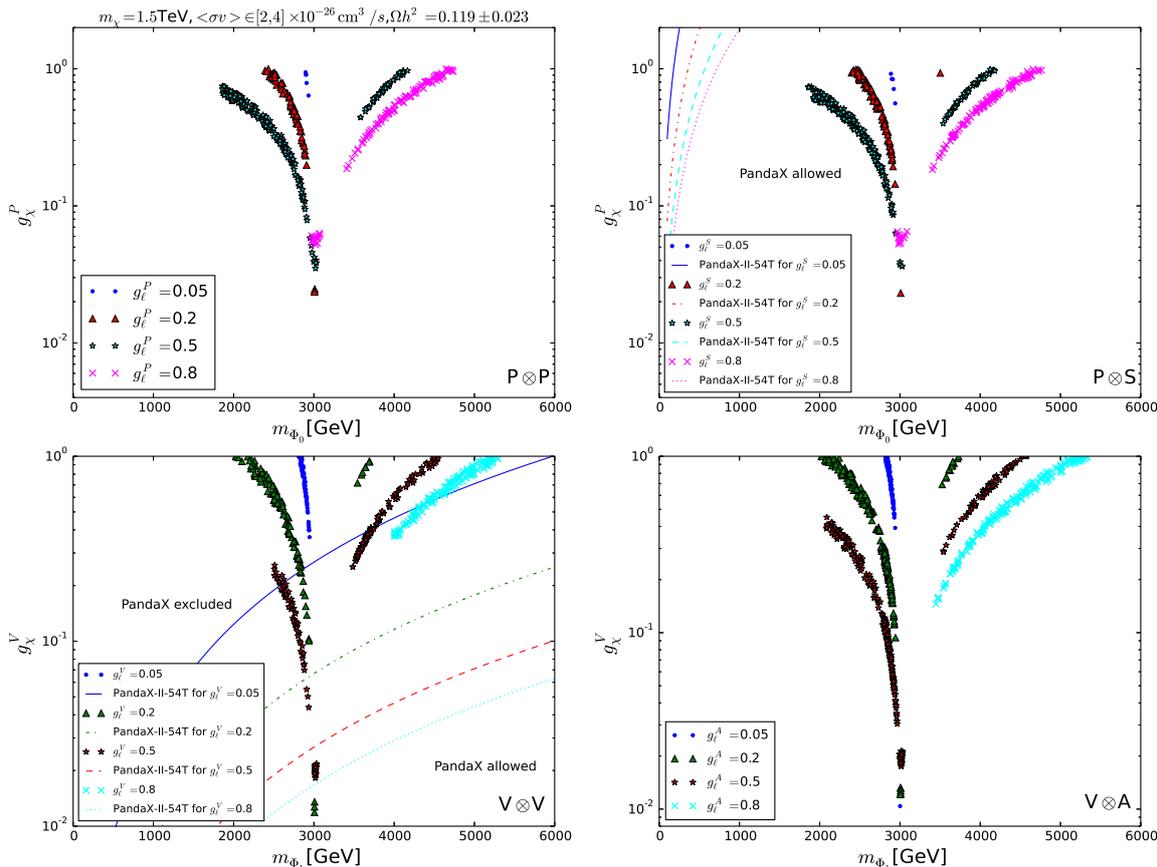


Figure 4. Scatter plots of the samples satisfying the DM relic density within 2σ range of Planck observed value, LEP bound and the DAMPE excess, projected on the plane of g_χ versus m_Φ for $g_\ell = 0.05, 0.2, 0.5, 0.8$. All samples are required to produce averaged annihilation cross-section $\langle\sigma v\rangle$ today within $(2-4) \times 10^{-26} \text{ cm}^3/s$. The 90% C.L. exclusion limits from the current PandaX-II data is also shown [61].

the DM has no interactions with nucleus. The surviving samples for $V \otimes V$ coupling are largely excluded by the PandaX-II limits of DM-nucleus scattering. There are also limits from other direct detection experiments such as XENON1T [62] and LUX [63]. However, their current bounds are weaker than that of PandaX-II.

It should be mentioned that the vector mediator Φ_1 can be produced at the LHC because of the loop-induced coupling between the mediator and light quarks, as shown in figure 5. The cross section in the narrow width limit is given by [64]

$$\sigma_{pp \rightarrow l^+ l^-} = \frac{\pi BR_{\Phi_1 \rightarrow l^+ l^-}}{3s} \sum_q C_{q\bar{q}}(m_{\Phi_1}^2/s) \left(g_q^{V^2} + g_q^{A^2} \right), \quad (3.4)$$

where $BR_{\Phi_1 \rightarrow l^+ l^-}$ is the branching ratio of the decay $\Phi_1 \rightarrow l^+ l^-$. The parton luminosity $C_{q\bar{q}}(m_{\Phi_1}^2/s)$ for the quark q reads

$$C_{q\bar{q}}(y) = \int_y^1 dx \frac{f_q(x) f_{\bar{q}}(y/x) + f_q(y/x) f_{\bar{q}}(x)}{x}, \quad (3.5)$$

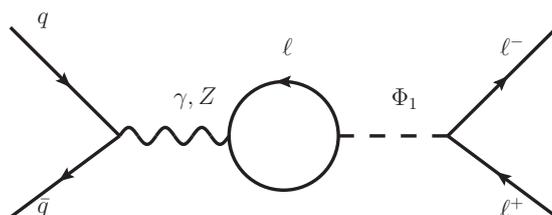


Figure 5. Feynman diagrams for the Drell-Yan process induced by a vector mediator Φ_1 at the LHC.

	$(g_\chi^V, g_\ell^V) = (0.21, 0.05)$	$(g_\chi^V, g_\ell^V) = (0.012, 0.2)$	$(g_\chi^V, g_\ell^V) = (0.2, 0.5)$
$m_{\Phi_1}=3\text{TeV}$	5.2×10^{-4}	7.5×10^{-3}	5.0×10^{-2}

Table 2. The cross section of dilepton production $pp \rightarrow \Phi_1 \rightarrow \ell^+ \ell^-$ at 13 TeV LHC, where the cross sections are in unit of fb. The benchmark points satisfy the DM relic density, the DAMPE $e^+ + e^-$ flux excess and the PandaX limits.

$m_\Phi(\text{TeV})$	$(g_\chi^V, g_\ell^V) = (0.012, 0.2)$	$(g_\chi^V, g_\ell^A) = (0.6, 0.2)$	$(g_\chi^P, g_\ell^P) = (0.6, 0.2)$	$(g_\chi^P, g_\ell^S) = (0.6, 0.2)$
2.1	—	-4.27×10^{-12}	-2.31×10^{-11}	2.31×10^{-11}
2.5	—	-2.78×10^{-12}	-1.65×10^{-11}	1.65×10^{-11}
3.0	4.13×10^{-13}	-2×10^{-12}	-1.14×10^{-11}	1.14×10^{-11}
3.6	—	-1.43×10^{-12}	-8.36×10^{-12}	8.36×10^{-12}

Table 3. Same as table 2, but for the corrections to the anomalous magnetic moment of the muon Δa_μ .

with $f_{q,\bar{q}}(x)$ being the quark and antiquark parton distribution function (PDF). We use MRST [65] to calculate the PDFs. The loop-induced couplings to quarks g_q^V and g_q^A are evaluated with package runDM [66]. The renormalization scale of the PDF and the couplings to quarks is set at m_{Φ_1} . We choose some benchmark points that satisfy the DM relic density, the DAMPE $e^+ + e^-$ flux excess and the PandaX limits and calculate the corresponding cross section of the dilepton process $pp \rightarrow \Phi_1 \rightarrow \ell^+ \ell^-$ at the 13 TeV LHC, as given in table 2. We note that they are much lower than the current LHC-13 TeV sensitivity [67]. We also evaluate the associated production processes $pp \rightarrow \ell^+ \ell^- \Phi_{0,1}$ and find they are negligibly small.

In table 3, we give the corrections to the muon $g - 2$ that arise from our leptophilic interactions [68]. It can be seen that the couplings $V \otimes V$ and $P \otimes S$ can produce a positive correction, which, however, is less than the value required by explaining the deviation of the muon $g - 2$ from its experimental measurement.

4 An $U(1)_X$ realization

An example of realizations of LDM, we introduce a Dirac fermionic DM field (χ) by imposing a Z_2 symmetry, under which all SM matter particles are even while χ is odd.

	Q_L^a	U_R^a	D_R^a	L_L^a	e_R	μ_R	τ_R	S	T	F	χ
$U(1)_X$	0	0	0	1	1	1	1	Q_S^X	0	Q_F^X	0
$U(1)'$	0	0	0	0	0	0	1	0	Q_T'	Q_F'	Q_χ'

Table 4. The $U(1)_X$ quantum number for SM matter contents with the generation index $a = (1, 2, 3)$. The complex scalars S and T are introduced to break the $U(1)_X$ and $U(1)'$ gauge symmetry, respectively. The Dirac fermion F that has charges of $U(1)$, is introduced to generate kinetic mixing between the two $U(1)$ gauge bosons.

Besides, we add a new $U(1)_X$ gauge interactions for leptons only, with the corresponding gauge quantum numbers shown in table 4. The complex scalars S and T are introduced to break the $U(1)_X$ and $U(1)'$ gauge symmetry, respectively.

Such an assignment will cause the $U(1)_X$ to be anomalous if there are no additional chiral fermions that are charged under $U(1)_X$ other than the SM matter contents. One possible way is to introduce new matter particles to cancel the anomaly. For example, we can add the fourth chiral-like family with non-trivial $U(1)_X$ quantum number, which satisfies the anomaly cancelation condition

$$\sum_i (3n_i + m_i) + 3k + l = 0, \tag{4.1}$$

with n_i, m_i, k, l being the $U(1)_X$ quantum numbers for quarks(n_i), leptons(m_i) of the first three family and the fourth family quarks(k) and leptons (l), respectively, such as $l = -3m$ with universal $m_i \equiv m$ for e, μ, τ leptons and trivial quantum numbers for all quarks. The fourth family can be very heavy by mixing with heavy vector-like fermions and can be compatible with current collider constraints.

Since the DM direct detection experiments will give stringent constraints, we require that the Dirac fermion DM χ will not carry $U(1)_X$ quantum number but will transform non-trivially under an additional $U(1)'$ gauge symmetry. Such $U(1)'$ gauge symmetry will be broken by additional complex scalar field T . The couplings between DM and lepton pairs will be induced through kinetic mixing between $U(1)_X$ and $U(1)'$. Given the gauge interaction $U(1)_X$ is universal for all kinds of leptons, we can anticipate that the decay products will lead to equal final states lepton species. This approach is similar to vector-portal DM scenario. Since the DM is vector-like, there will be no additional anomaly in the model. New scalar T or vector-like fermion F , which transform non-trivially under both $U(1)_X$ and $U(1)'$, will induce non-trivial mixing between the two new $U(1)$ gauge symmetry through the following interactions,

$$\begin{aligned} \mathcal{L} \supseteq & |D_\mu S|^2 + |D_\mu T|^2 - m_S^2 |S|^2 - m_T^2 |T|^2 - \lambda_1 |S|^4 - \lambda_2 |T|^4 \\ & - \lambda_3 |S|^2 |T|^2 + i\bar{F}\gamma^\mu D_\mu F - m_F \bar{F}F, \end{aligned} \tag{4.2}$$

with

$$\begin{aligned} D_\mu F &= (\partial_\mu - iQ_F^X g_X A_\mu^X - iQ_F' g' A'_\mu)F, \\ D_\mu S &= (\partial_\mu - iQ_S^X g_X A_\mu^X)S, \\ D_\mu T &= (\partial_\mu - iQ_T' g' A'_\mu)T. \end{aligned} \tag{4.3}$$

As mentioned above, an odd Z_2 parity is imposed for the Dirac fermion χ to act as a viable DM candidate. The masses of the scalar T are assumed to be heavier than the DM mass so that the DM will not annihilate into them. We should note that in the scalar potential, possible terms involving standard model Higgs fields H as $(T^\dagger T)(H^\dagger H)$, $(S^\dagger S)(H^\dagger H)$ etc could appear. Such terms could contribute to the DM direct detection at two loop level.

The kinetic mixing between two gauge bosons can be parameterized as

$$\mathcal{L} \supseteq -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_1^2 A_\mu A^\mu - \frac{1}{2}m_2^2 A'^\mu A'_\mu, \quad (4.4)$$

with

$$\epsilon = -\frac{g_X g'}{12\pi^2} Q_F^X Q'_F \log\left(\frac{m_F^2}{\mu^2}\right), \quad (4.5)$$

after integrating out heavy fermion loops, or

$$\epsilon = \frac{g_1 g_2}{48\pi^2} Q_F Q'_F \log\left(\frac{m_S^2}{\mu^2}\right), \quad (4.6)$$

after integrating out possible heavy scalar loops.

The matrix to remove the mixing is given as

$$\begin{pmatrix} \tilde{A}_\mu \\ \tilde{A}'_\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1+\epsilon^2}} & 0 \\ -\frac{\epsilon}{\sqrt{1+\epsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} A_\mu \\ A'_\mu \end{pmatrix}, \quad (4.7)$$

with the Lagrangian involving the mass mixing

$$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} - \frac{1}{2}m_1^2 \tilde{A}_\mu \tilde{A}^\mu - \frac{1}{2}m_2^2 \tilde{A}'_\mu \tilde{A}'^\mu - m_1^2 \epsilon \tilde{A}_\mu \tilde{A}'^\mu. \quad (4.8)$$

Assuming identical masses for the scalars $m_1^2 = m_2^2$, we obtain

$$(\bar{\chi}\gamma^\mu\chi) (\bar{L}\gamma^\nu L) [\epsilon/m_2^2]. \quad (4.9)$$

To explain the DAMPE excess without conflicting with direct detection experiments, we can choose $m_2 \simeq 3 \text{ TeV}$ and the mixing parameter $\epsilon \approx 1.0 \times 10^{-2}$. Such values can be obtained by requiring $g_1 = g_2 \approx 0.3$ with $Q_1 = Q_2 = 1$.

5 Conclusion

In this work, we explained the recent DAMPE cosmic $e^+ + e^-$ excess in simplified leptophilic Dirac fermion dark matter (LDM) framework with a scalar (Φ_0) or vector (Φ_1) mediator. We found that the couplings $P \otimes S$, $P \otimes P$, $V \otimes A$ and $V \otimes V$ can fit the DAMPE data under the constraints from gamma-rays and cosmic-rays. However, for the $V \otimes V$ coupling, due to the stringent constraints from the PandaX-II data, the surviving samples only exist in the resonance region, $m_{\Phi_1} \simeq 2m_\chi$. But for other couplings, the direct detection bounds can easily be evaded. We also studied the possible collider signatures of LDM, such as the Drell-Yan process $pp \rightarrow \Phi_1 \rightarrow \ell^+ \ell^-$, and the muon $g - 2$. In the end, we constructed an U(1) extension of the SM to realize our simplified LDM model.

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